The Development of Inflatable Array Antennas

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Abstract

Three inflatable array antennas recently developed for spacecraft applications are a 3.3m x 1.0m L-band synthetic aperture radar (SAR) array, a 1.0m-diameter X-band telecom reflectarray, and a 3m-diameter Ka-band telecom reflectarray. All three antennas are similar in construction and each consists of an inflatable tubular frame that supports and tensions a multi-layer thin-membrane RF radiating surface with printed microstrip patches. The L-band SAR array achieved a bandwidth of 80 MHz, an aperture efficiency of 74%, and a total mass of 15 kg. The X-band reflectarray achieved an aperture efficiency of 37%, good radiation patterns, and a total mass of 1.2 kg (excluding inflation system). The 3m Ka-band reflectarray achieved a surface flatness of 0.1mm RMS, good radiation patterns, and a total mass of 12.8 kg (excluding inflation system). These antennas demonstrated that inflatable arrays are feasible across the microwave and millimeter-wave spectrums. Further development of these antennas are deemed necessary, in particular, in the area of qualifying the inflatable structures for space environment usage.

Introduction

JPL/NASA's Earth remote sensing and deep-space exploration programs have increasing demand for spacecraft high-gain and large aperture antennas. At the same time, however, low mass and small stowage volume are emphasized on these antennas in order to reduce payload weight and size and thus reduce launch cost. To meet these goals, large-aperture antennas must be deployable. One deployable concept using an inflatable parabolic reflector [1] was introduced about two decades ago and was demonstrated in a recent space shuttle experiment [2]. However, the full implementation of this concept is still hampered by the inability to achieve and maintain the required surface accuracy. Even with a rigidizable membrane and an inflatable support structure, it is believed that it will be difficult to maintain the desired surface accuracy of a large parabolic aperture for the duration of a long space flight. To mitigate the difficulty associated with curved surfaces, a new class of planar array technology is being developed [3,4]. It is believed that it will be significantly simpler to maintain the required surface tolerance of a flat "natural" surface, such as a planar array, than a curved "non-natural" surface, such as a parabolic reflector. In addition, a planar array offers the possibility of wide-angle beam scanning, which cannot be easily achieved by a parabolic reflector.

At JPL, three inflatable planar array antennas have recently been developed. Most of the RF capabilities and a portion of the mechanical capabilities of these antennas have been demonstrated for space application. These three antennas are the 3.3m x 1.0m L-band SAR array [5] for Earth remote sensing application, the 1.0m-diamater X-band reflectarray [6] and the 3m-diameter Ka-band reflectarray [7] for deep-space telecom application. The RF design and the aperture membrane surface of these antennas were developed at JPL, while the development of the inflatable structures and the antenna integration were accomplished by ILC Dover, Inc. and L'Garde Corp.

Antenna Description and Performance

All three inflatable antennas are constructed and deployed in a similar fashion. Each antenna is basically constructed from an inflatable tubular frame that supports and tensions a multi-layer thin-membrane RF radiating surface with many printed microstrip patch elements. All three antennas are deployed by a "roll out" mechanism as a carpet is rolled out. The folding mechanism is not used here to avoid forming large creases on the printed patch elements and transmission lines. Any large crease may significantly degrade the RF performance. All three antennas were developed as breadboards for the purpose of initial technology demonstration to assure that the inflated thin membrane can indeed yield proper RF performance. Several technologies remain to be developed in the future to allow these antennas to be used in the space environment. The detailed description and performance of these antennas are separately presented in the following subsections.

L-Band SAR Array

Antenna Description – The inflatable L-band SAR array, having an aperture size of 3.3m x 1.0m, is a technology demonstration model with 1/3 the size of the future full size (10m x 3m) array. Two such inflatable arrays were recently developed: one by ILC Dover, Inc. and the other by L'Garde Corp. The ILC Dover unit is shown in Fig. 1, and the L'Garde unit is given in Fig. 2. Both units are very

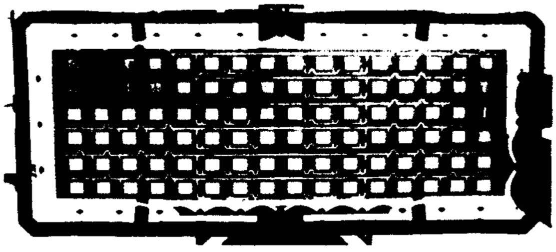

Figure 1. Inflatable L-band SAR array developed by JPL/ILC Dover Inc.

Figure 2. Inflatable L-band SAR array developed by JPL/L'Garde Corp.

similar and each basically is a rectangular frame of inflatable tubes that support and tension a three-layer thin-membrane radiating surface with microstrip patches and transmission lines. A portion of the RF design of the three layers is shown in Fig. 3. The inflatable tube of the ILC

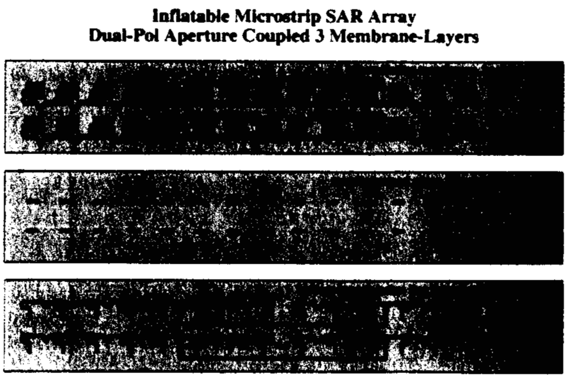

Figure 3. RF designs of the three membrane layers

Dover unit has a diameter of 13 cm and is made of 0.25mm-thick urethane coated Kevlar material. The L'Garde's inflatable tube has a diameter of 9 cm and is made of 0.08mm-thick rigidizable stretched aluminum material. The rigidizable tube is used to avoid the need of constant air pressure and the concern of air leakage due to space debris damage. The three membrane layers are separated 1.27 cm between the top radiator layer and the middle ground-plane layer and 0.635 cm between the middle layer and the bottom transmission-line layer. The connection between these membranes and the inflated tubular frame is made by a series of catenary attachment points and tension cords. The required spacings between the three membranes are maintained by the tension of the catenary cords, the honeycomb spacing panels and bars, and small spacing blocks at each of the catenary points. The membrane material used is a thin film of 5-micron-thick copper cladding on a 0.13-mm-thick Kapton dielectric material.

Antenna test results – The L'Garde unit achieved a total antenna mass of 11 kg with an average mass density of 3.3 kg/m^2. The ILC Dover unit has a slightly higher mass. The surface flatness of the L'Garde unit was measured to be ± 0.28 mm and is better than the requirement of ± 0.8 mm. The ILC Dover's surface flatness was measured to be ± 0.7 mm. Both antenna units achieved bandwidths slightly wider than the required 80 MHz, and achieved port isolation between the two orthogonal polarizations of greater than 40 dB within the required bandwidth. The radiation patterns of the ILC Dover unit measured in both principal planes at 1.25 GHz are given in Figs. 4 and 5.

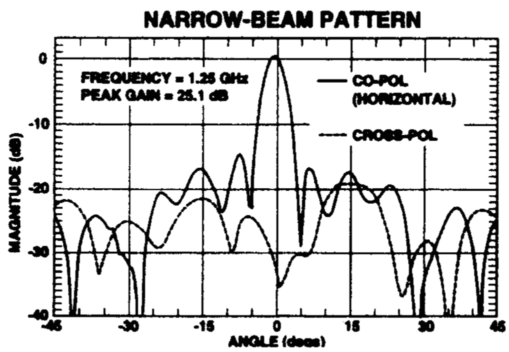

Figure 4. Measured pattern of the inflatable SAR array along the aperture's long dimension.

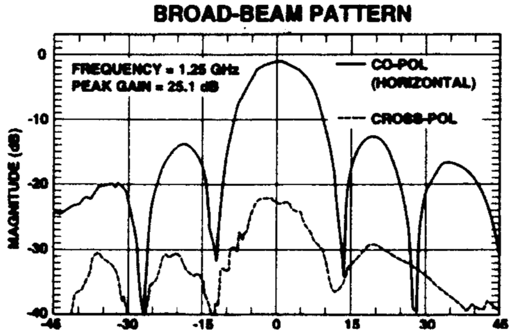

Figure 5. Measured pattern of the inflatable SAR array along the aperture's short dimension.

Sidelobe levels of −14 dB in the azimuth plane and −12 dB in the elevation plane are reasonable for this uniform distributed array. The cross-pol level of less than −20 dB within the main beam region is also considered acceptable for this radar application. Pattern measured at frequencies from 1.21 GHz to 1.29 GHz are very similar to those shown in Figs. 4 and 5 without significant degradation. The measured peak gain of ILC Dover's unit is 25.2 dB at 1.25 GHz, which corresponds to an aperture efficiency of 52%. L'Garde's unit has a peak gain of 26.7 dB and an aperture efficiency of 74%. The better efficiency of L'Garde's unit is the result of better surface tolerance and more precise membrane spacing. Nevertheless, both units are considered quite good as they are the first demonstration models ever built.

X-Band 1-m Reflectarray

Antenna description -- The inflatable X-band reflectarray antenna [6], shown in Fig. 6, has an inflated torus tube that

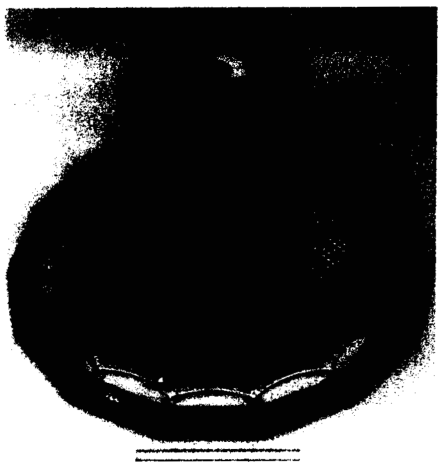

Figure 6. 1m X-band inflatable reflectarray

supports and tensions the one-meter-diameter two-layer-membrane reflectarray surface. The antenna's overall RF system and the aperture membrane surface were designed at JPL, while the inflatable structure and antenna integration were developed by ILC Dover, Inc. The inflated tripod tubes are attached to the torus as struts to support a feed horn. The inflatable tubes are made of 0.25mm-thick urethane coated Kevlar material and the reflectarray membrane material is made of 5-micron-thick copper cladding on 0.05mm-thick Kapton. There are a total of two membrane layers separated by 1.3 mm. The top copper layer was etched to produce approximately 1,000 isolated microstrip patches, while the un-etched bottom layer serves as the ground plane. Many small foam discs (7 mm diameter) are placed between the two membranes as means of maintaining the required uniform membrane spacing.

Antenna test results -- This inflatable antenna structure achieved a mass of 1.2 kg, which excludes the mass of the inflation system and the feed horn. With future development, it is believed that the mass of the inflation system for this particular antenna size can be on the order of 0.5 kg. The microstrip patches on the top layer membrane are all square in shape and identical in size, but with different-length phase-delay lines attached. These phase-delay lines are used to compensate for the differential phases of the different path lengths from the feed horn to all the patches [8]. Each patch has two equal-length phase-delay lines orthogonally attached. With the feed horn left-hand circularly polarized, the re-radiated fields from the patches are right-hand circularly polarized. A measured antenna elevation pattern at 8.3 GHz is given in Fig. 7 where the peak sidelobe level (-19 dB) and peak cross-pol level (-19 dB) are both acceptable to the communication system. However, the peak sidelobe of −19 dB is higher than the expected −25 dB. This is primarily due to the blockage effects of the feed and feed support struts. The main beam of the antenna has a −3 dB beamwidth of 2.4° which is expected from a circular aperture of 1m diameter. The antenna also achieved the expected −1 dB gain-bandwidth of 250 MHz (about 3%).

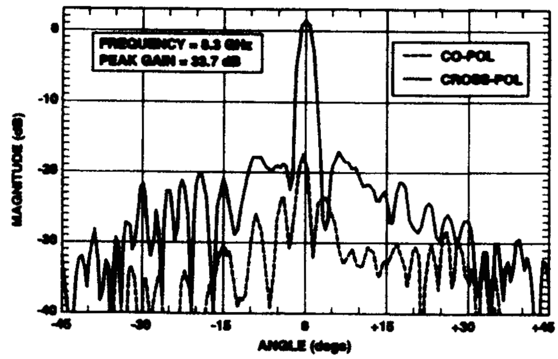

Figure 7. Measured radiation pattern of the inflatable X-band 1m reflectarray

The measured peak gain at 8.3 GHz is 33.7 dBi which implies an antenna efficiency of 37%. The expected efficiency from an X-band 1m aperture should be about 50%. The relatively poor efficiency achieved by this inflatable reflectarray is primarily due to design and manufacturing inexperience in building this first demonstration model. Imperfect separation between membranes, feed and strut blockage, surface roughness, leakage radiation from phase delay lines are all contributors to the inefficiency. All these errors are believed to be correctable for future models.

Ka-Band 3-m Reflectarray

Antenna description -- A photograph of the inflatable Ka-band reflectarray antenna with a 3-m-diameter aperture is shown in Fig. 8. This antenna, similar to the above X-

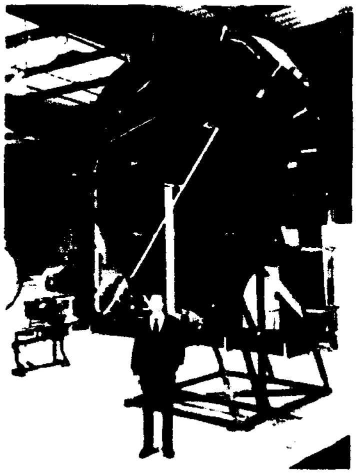

Figure 8. 3m Ka-band inflatable reflectarray

band reflectarray, was co-developed by JPL and ILC Dover, Inc. It consists of a horse-shoe shaped inflatable tube that supports and tensions the 3-m aperture membrane. The tube, 25 cm in diameter, is made of urethane coated Kevlar and is inflated to 3.0 psi pressure, which translates to about 90 psi of tension force to the aperture membrane. The inflatable tube is connected to the aperture membrane at 16 catenary points with spring-loaded tension cords. Each connecting point has displacement adjustment capability in the x, y, z directions so that the circumference of the circular aperture membrane can be made into a single plane orthogonal to the feed horn axis. The single-layer aperture membrane is a 5-mil (0.13 mm) thick Uplex™ dielectric material (a brand of polyimide) with both sides clad with 5-micron thick copper. The copper on one side was etched to form approximately 200,000 microstrip patch elements, while the copper on the other side is un-etched and serves as the ground plane for the patch elements. The inflatable tripod tubes, asymmetrically located on the top portion of the horse-shoe structure, are used to support a Ka-band corrugated feed horn. The horse-shoe-shaped main tube structure and the asymmetrically connected tripod tubes are uniquely designed in geometry to avoid membrane damage and flatness deviation when the deflated antenna structure is rolled up.

Antenna test results – The antenna's RF tests were performed at the in-door compact range of Composite Optics, Inc. (COI). A typical elevation pattern of the antenna is given in Fig. 9 where a 0.22° beamwidth was measured. The sidelobe level is –30 dB or lower below the main beam peak, and the cross-pol level is –40 dB or lower. All patch elements are circularly polarized and are identical in dimensions. Their angular rotations [9] are different and are designed to provide correct phase delays to achieve a co-phasal aperture distribution. The antenna

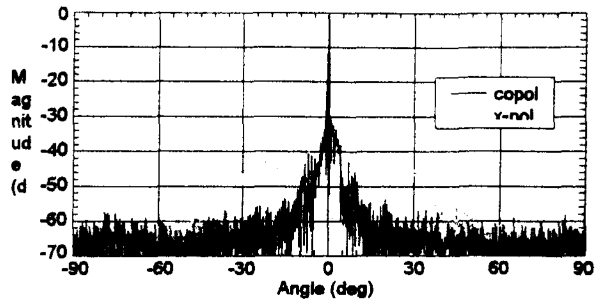

Figure 9. Measured radiation pattern of the 3m Ka-band inflatable reflectarray

gain was measured versus frequency. The results show that the antenna is tuned at the desired frequency of 32.0 GHz with a –3 dB bandwidth of 700 MHz. A peak gain of 50 dBic was measured and is significantly lower than the expected value of 56 dBic. This measured gain indicates an aperture efficiency of only 10% which is far from the expected 40%. This unexpectly low efficiency was the result of a design flaw. The phase delay lines that attached to each patch element have very poor impedance match to the patch and, thus, cause a poor radiation efficiency. A second iteration development has been initiated to correct this design flaw. Although the aperture efficiency was poor, the achievement of excellent membrane flatness indicates that inflatable array antenna at Ka-band is now feasible.

Comparison with Other Types of Deployable Antennas

In addition to the inflatable type, there are several other types of previously developed deployable antennas that achieved comparable or better mass densities. All these antennas are of the reflector type and achieved low masses with conductive mesh as their reflecting surfaces. One is the Hoop/Column mesh reflector [10] developed by Harris Corp. The other is the Wrapped-Rib mesh reflector [11] developed by Lockheed Corp. The third one, a more recent development, is the AstroMesh reflector developed by Astro Aerospace Corp. The AstroMesh achieved a mass density of less than 1.5 kg/m^2 which is slightly lower than the inflatable antennas. Although these mesh deployable antennas can achieve small mass densities, they are of the parabolic reflector type and cannot be made into the array type and, thus, cannot achieve wide-angle beam scan. In order for a mesh type of reflector to deploy, many mechanical devices are needed, such as motors, actuators, springs, tension cords, etc. More devices generally imply less reliability and more cost. In addition, due to the roughness of the mesh surface, the mesh reflector has not been proven to function at millimeter-wave frequencies.

In addition to the mesh reflector, the inflatable antenna should also be compared with another type of low-mass antenna: the foldable panel array. The foldable panel array has been mostly used for SAR radar applications, such as the U.S. SeaSAT and SIR-A,B,C series, the Japanese JERS, the European ERS-1, and the Canadian RadarSAT. Some of these antennas even used low-mass honeycomb as their primary panel material. However, due to their heavy deployment motor system and their heavy structure support system, these foldable panel antennas all have a total mass larger than 250 kg or a mass density larger than 10 kg/m^2. Table 1 shows a relative comparison between inflatable, mesh, and panel types of antennas.

	Inflatable	**Mesh**	**Panel**
Mass	low	low	high
Reliability	high	low	medium
Packing efficiency	high	medium	medium
Cost	low	high	medium

Table 1. Comparison of three types of deployable antennas

Future Challenges

The basic structure of an inflatable array is a multilayer planar aperture surface that is supported and tensioned, through a catenary system, by several inflated tubular elements. In order to successfully develop an inflatable array antenna at any frequency throughout the microwave and millimeter-wave spectrums and with any aperture size from several meters to tens of meters, several technical challenges must be addressed and resolved. These challenges are separately discussed in the following subsections:

Membrane Flatness and Separation

In order for a planar array to maintain certain required aperture efficiency and sidelobe/cross-pol levels, the aperture membrane must maintain certain flatness accuracy. This required flatness, depending on the requirements, should generally be between 1/20th and 1/40th of a free-space wavelength. For a multilayer membrane aperture, specific membrane separation distances must also be maintained, especially for a microstrip array. If microstrip patches are separated with slightly different distances from their ground plane, they will resonate at different RF frequencies, which implies a very inefficient array aperture at the required operating frequency. Generally, the required membrane separation tolerance should be smaller than 1/20th of the absolute separation distance.

The above stringent flatness requirement is currently being addressed primarily by the tension force of the inflatable tube. The tighter the flatness requirement, the larger the tension force required, which implies that a larger inflation tube and stronger tube material are needed. All these will result in larger antenna mass which is undesirable. The required membrane separation tolerance is currently met by, in addition to the tension force, using sparsely located small spacers. Tighter separation tolerance implies that larger tension force and more spacers are needed, which also implies larger antenna mass. In the future, innovative techniques are needed for maintaining the required membrane flatness and layer separation without increasing significantly the antenna mass.

Tube Rigidization Technique

For any long-term space application, the inflatable tube needs to be rigidized once it is inflated in space. This is to avoid deflation and loss of tension force due to leaks in the inflatable caused by impacting micrometeoriods and space debrids. If the inflatable tubes are rigidized upon the completion of deployment, the need to carry a large amount of make-up gas to compensate for the leaks can thus be eliminated.

There are several rigidization techniques. One early technique was enabled by the development of several polymers that can be cured by space environments [10], such as vacuum, ultraviolet (UV) light, cold temperature, etc. A second technique is the use of stretched aluminum [11]. When thin aluminum foil is stretched by inflation pressure just above the aluminum's yield point, it rigidizes. Unfortunately, when the thin-wall aluminum tube becomes very long, it cannot carry large non-axial or bending loads. Aluminum with reinforced laminate material needs to be investigated. The third method is called hydro-gel rigidization [12], which uses woven graphite fabric impregnated with a water-soluble resin (hydro-gel). When evaporation of the water content occurs in space vacuum environment, the dehydrated gel fabric rigidizes to give structural stiffness. This rigidization technique, as well as the stretched aluminum, are reversible processes, which will allow several ground deployment tests prior to space flight. The fourth technique uses heat-cured thermoplastic material. Heating wires or electric resistive wires are imbedded into a soft plastic material which rigidizes when heated to a certain temperature. This curing process is also reversible; however, it may require a large amount of electric power depending on the size of the inflatable structure.

All the above techniques have certain advantages, as well as disadvantages. They require continued investigation and improvement. Their performance parameters, such as mass density, curing time, bending stiffness, etc., need to be subjected to a tradeoff and an optimal technique can thus be selected for a particular mission. Regardless of the rigidization technique, one major challenge is for a particular technique to assure that the deployed structure after rigidization maintain its original intended structure shape and surface accuracy.

Controlled Deployment

In a space mission, there is a high probability that an uncontrolled inflation of a large inflatable structure might lead to self-entanglement, as well as damage to other spacecraft hardware. There are several controlled development mechanisms. One uses the compartmental valve control technique where the long inflatable tube is divided into a series of sectional compartments with a pressure-regulated valve installed at the beginning of each compartment. As the inflation gas enters, the tube gets sequentially deployed in a controlled manner. A second mechanism uses long coil springs which are embedded along the inner walls of the inflatable tube. A controlled deployment of the tube is achieved by balancing the inflation pressure and the restoring force of the spring. The third technique is to use a long Velcro Strip glued to the outside and along the long dimension of the tube wall. As the tube becomes inflated, the Velcro strip provides a certain amount of resistance force and thus achieves the controlled deployment. This technique, which already has space flight heritage, offers a significant advantage over the coil spring method because the Velcro strip, unlike the coil spring, will not impose any restoring force on the deployed tube when the inflation deployment is completed. The fourth technique of controlled deployment, proposed by L'Garde Corp., involves the use of a mandrel. During the deployment process, the inflation tube is forced to go over a guiding mandrel, which introduces a frictional force to balance the inflation pressure and to achieve the controlled deployment.

The above controlled deployment mechanisms must continue be improved and innovative concepts should be developed to minimize the mechanism's mass and risk impacts to the overall antenna system.

Packaging Efficiency

The inflation deployment techniques currently used for array type antennas are limited to the roll-up mechanism. No folding of the membrane is allowed, to avoid the formation of large creases and cracks in the very thin copper traces on the membrane surface. Therefore, when the antenna is rolled up, its packaged minimum-achievable dimension is the short dimension of a rectangular aperture or the diameter of a circular aperture. For examples, for a 10m by 3m aperture antenna, the packaged best-achievable dimension would be 3m long and for a 10m by 10m aperture, the best-packaged dimension would be 10m long, which can hardly fit into any current launch rocket. Therefore, it is imperative that innovative deployment techniques must be developed for future very large inflatable array antennas.

Membrane Mountable T/R Modules

One of the major advantages of the inflatable array antenna over that of the inflatable reflector antenna is that the array antenna has the capability of achieving wide-angle beam scanning. To achieve wide-angle beam scanning in both principle planes of a large array, many transmit/receive amplifier (T/R) modules with phase shifters need to be installed throughout the array aperture. Although current state-of-the-art technologies provide various miniaturized T/R modules, the packaged configurations of these modules, with significant mass and volume, preclude mounting onto the thin membrane surface. Very thin and low mass T/R modules should be developed in the future to preserve the beam scanning capability of the array antenna.

Modeling and Simulation of Static and Dynamic Space Environmental Effects

Inflatable antennas are a fairly new mechanical structure and their structural form may vary significantly from one antenna to another. Accurate mathematical modeling and simulation techniques must be developed to predict the in-space static and dynamic effects for a variety of inflatable antenna types. Orbital and deep space thermal effects may distort the shape of the inflatable tubes or fatigue the aperture membranes. Spacecraft maneuvering will induce a natural vibration of the inflatable structure, which may also distort or damage the antenna. The effects of these static and dynamic forces on the inflatable structure need to be well understood through calculation or simulation.

Conclusion

Three inflatable array antennas have been developed at the microwave frequencies of L-band and X-band, as well as at the millimeter-wave frequency of Ka-band. These antennas were developed to demonstrate that the inflatable array technology is feasible in reducing the mass and stowage volume of future spacecraft's high-gain and large-aperture antennas. To realize the inflatable array technology for space application, several challenges in the mechanical area remain to be resolved. The development of inflatable structure rigidization methods, controlled deployment techniques, space survivable membrane materials, and accurate mathematical structure analysis tools is necessary if successful space application is to be achieved.

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